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HINS Linac Front End
SS-1 Section Focusing Solenoid
Quench Protection Analysis

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Introduction

Previously published notes [1, 2] summarize the quench analysis made for HINS Linac Front End CH Section focusing solenoids. Analysis of events in a case of a quench in the main coil or in the bucking coils of a HINS Linac Front End CH Section focusing solenoid in the absence of a dump resistor in the solenoid discharge circuit was made in [1]. Use of a dump resistor for protection of focusing solenoids in the CH Section of the HINS Linac Front End was studied in [2].

This note presents results of a quench analysis and related quench protection studies made for focusing solenoid in the SS-1 section of the HINS Linac Front End. The results have been obtained by use of a modified MATLAB-based software described in [3]. A note describing modifications of this software will be published later.

There are two types of focusing solenoids in the superconducting section: with and without dipole correctors. A description of a solenoid design without correctors can be found in [4]. This design was just slightly modified later in order to take into account updated winding data and strand parameters. Much more modifications were required to add correctors to the design, but it did not result in dramatic changes of the solenoid geometry and coil parameters. Although a subject of this note is quench propagation in solenoids without correctors, the results can be applied to solenoids with embedded correctors. Protection of corrector windings is a separate issue; it was analyzed in [5].

In the first part of the note we will analyze events in a case of a quench in the absence of a dump resistor in the solenoid discharge circuit. In the second part of the note an optimal circuit configuration and a value of dump resistor will be found.

A model of the solenoid to analyze is shown in Fig. 1. Initiation of a quench is made by an appropriate elevation of temperature on a certain turn in a coil.

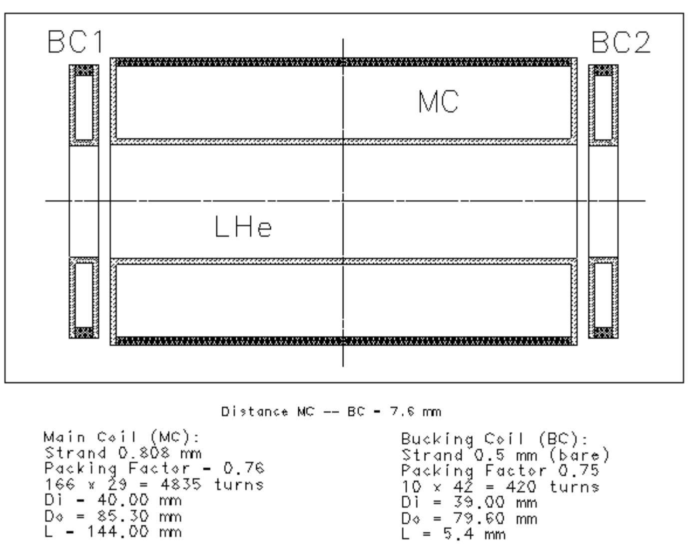


Fig. 1. A model used for quench propagation analysis

1 Quench analysis in absence of dump resistor

1.1 Quench in the main coil

1.1.1 Quench occurs in the point of the maximum field

The initial quench location is in the middle of the inner layer (layer #1, turn #83). Graphs in Fig. 2 below show time profiles of the coil current, maximum temperature, the coil resistance; in Fig. 3 one can find temperature distribution after the quench and voltage to ground during quenching. Two columns correspond to two different settings of the initial current:

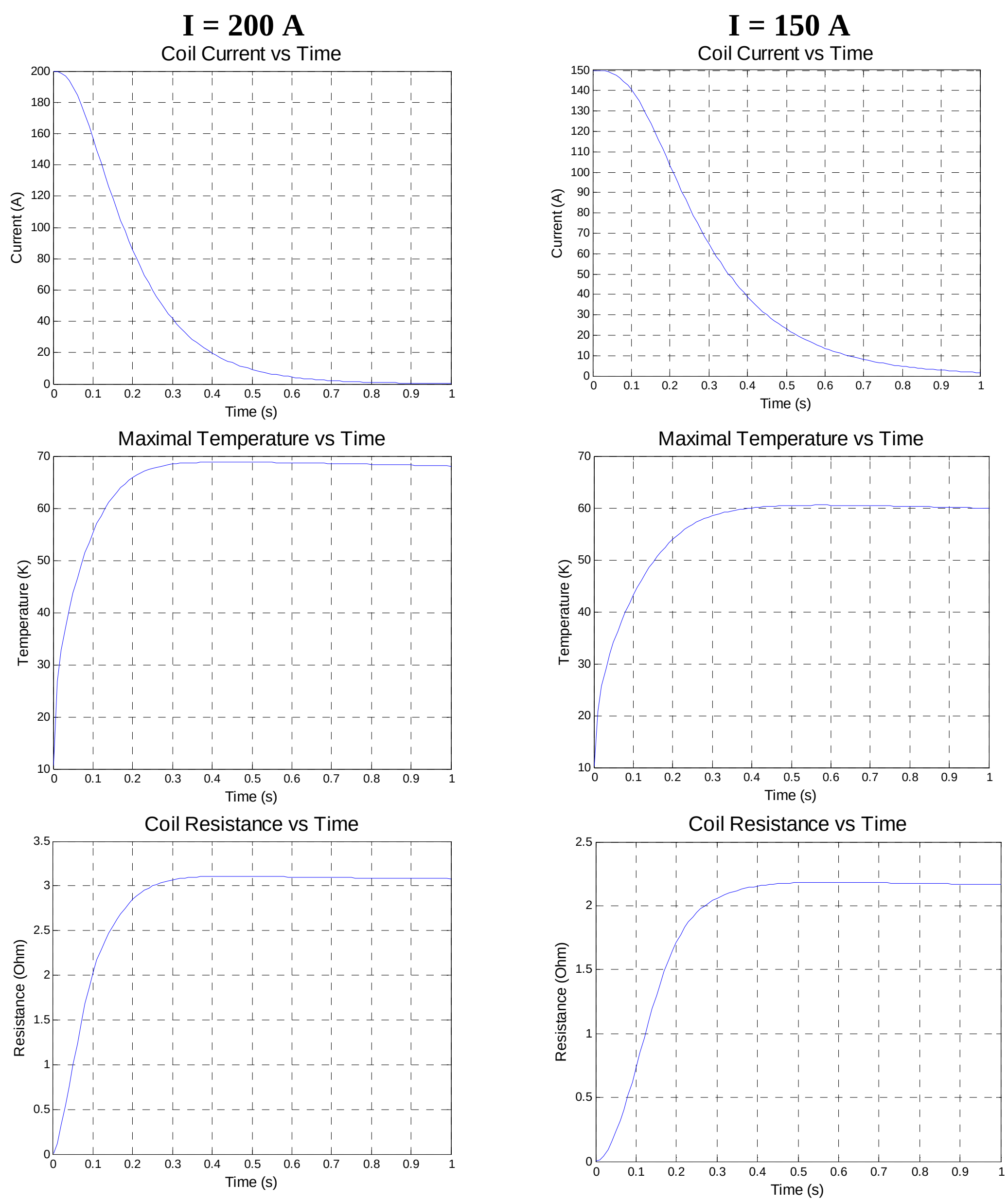


Fig. 2. Time profiles of the current, maximum temperature, and resistance of the main coil. Quench starts at the point of the maximum field.

I = 200 A **I = 150 A**

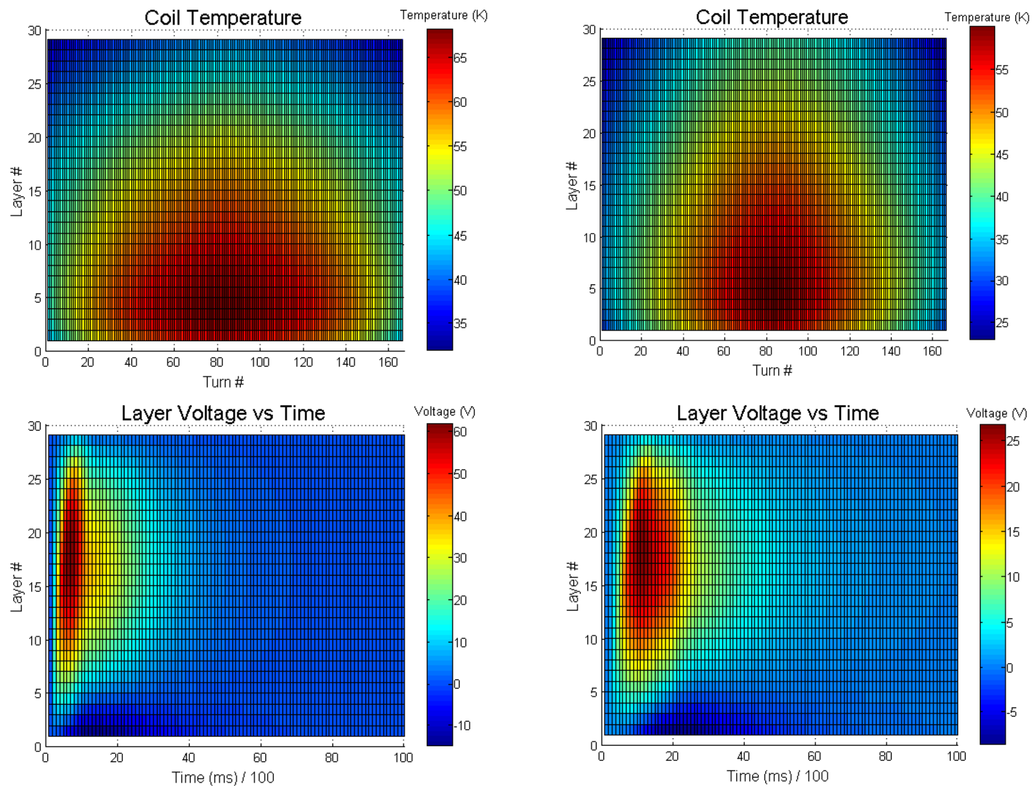


Fig. 3. The final temperature in the main coil and voltage to ground during quenching. Quench starts at the point of the maximum field.

The maximum voltage relative to ground in both cases develops in the middle layer of the coil and reaches ~62 V if the initial current is 200 A (~27 V if it is 200 A). This voltage is positive, which indicates the increase of the resistance of the internal layers due to heating and compensation of this voltage due to inductive component which develops when the current starts decaying. The voltage of the last layer is zero by definition if no dump resistance is used. Adding the dump resistance will significantly increase layer voltage.

It is possible to notice that although stored energy is almost 1.8 times lower in the case of the 150 A initial current, the maximum temperature is just ~13% lower. This happens because of the reduced quench propagation velocity due to lower magnetic field. Lower energy dissipates in smaller volume of the coil.

Similar situation can happen if the quench location is in the area where the magnetic field is low, so we need to test the main coils and the bucking coils taking this effect into the account.

1.1.2 Quench occurs in the point of the minimum field

The initial quench location is in the middle of the outer layer (layer #29, turn #83), where the magnetic flux density is close to zero. Fig. 4 below shows time profiles of the coil current, maximal temperature, and the coil resistance during quenching. Graphs in Fig. 5 show temperature distribution inside the coil after quench and layer voltage time profile. Two columns correspond to two different settings of the initial current:

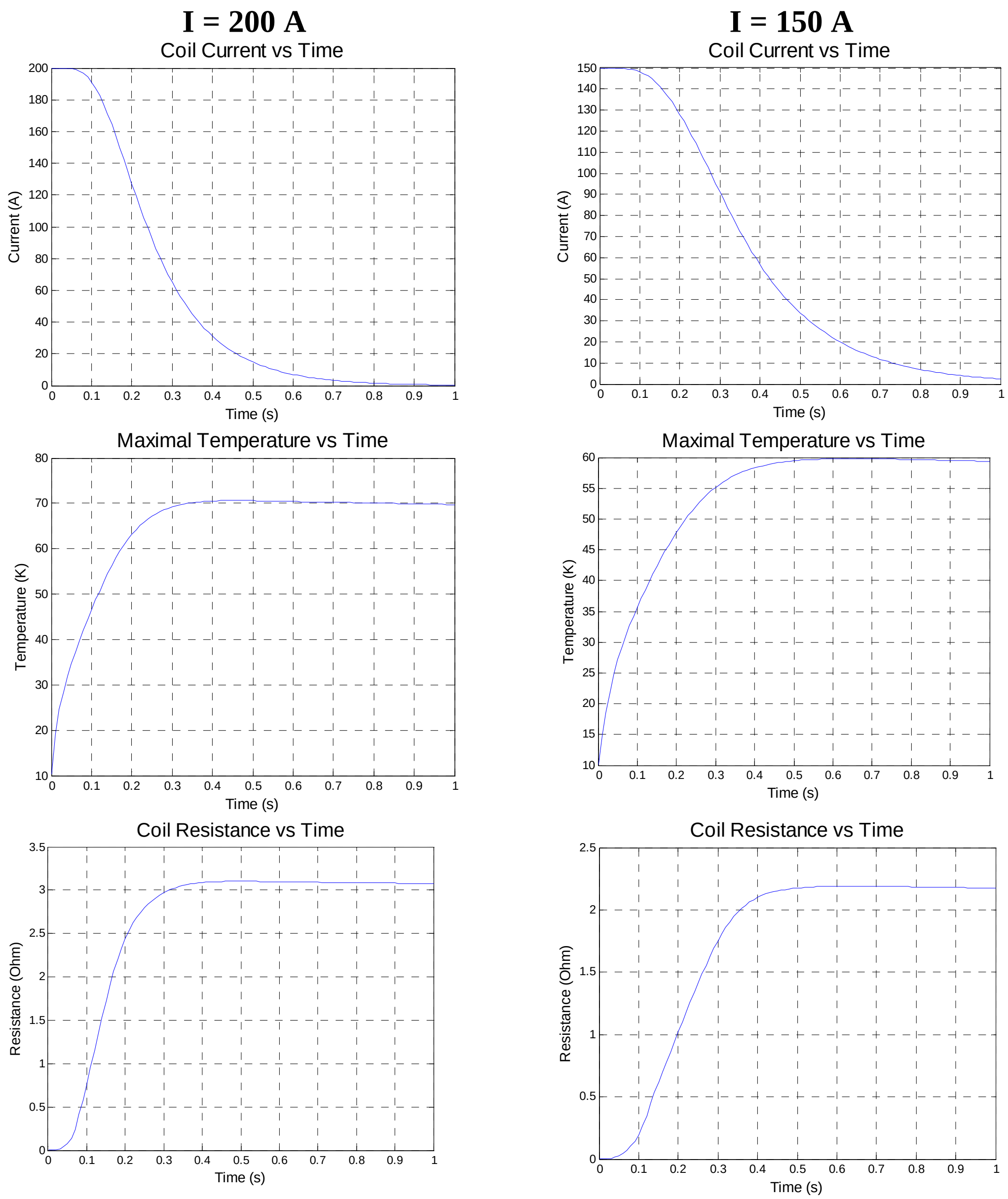


Fig. 4. Time profiles of the current, maximal temperature, and the resistance of the main coil during quenching. Quench starts at the point of the minimum field.

I = 200 A **I = 150 A**

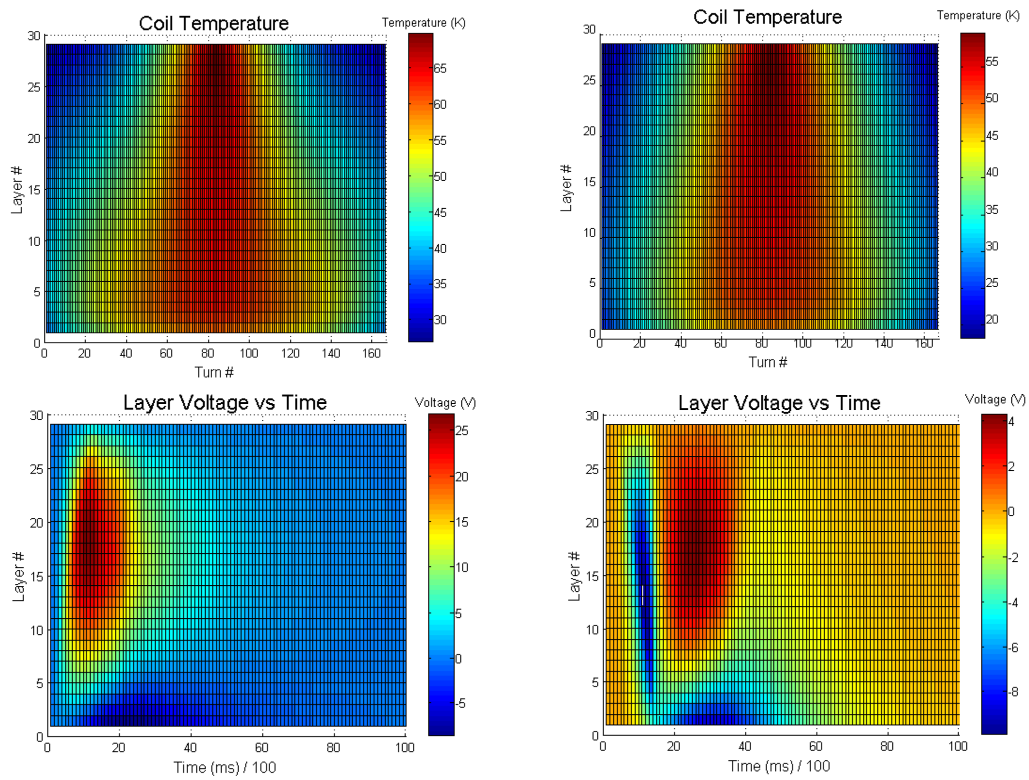


Fig. 5. Final temperature distribution in the main coil and layer voltage time profile. Quench starts at the point of the minimum field.

Analyzing the figures above, we can say that, although some details of the current and the coil resistance time profiles differ from what we saw in the case of the initial quench location in the area of the maximum field, global behavior of the coil did not change much: the maximum temperature is still ~ 70 K at 200 A initial current (~ 60 K at 150 A) and maximum coil resistance is ~ 3 Ohm at 200 A (2 Ohm at 150 A). Layer voltage profile differs from what we saw before. The voltage polarity can change from negative to positive because the quench starts in the outer layer, so the inner layers first see inductive voltage that is compensated (and over-compensated) later by the resistive voltage of the turns turning normal. This voltage is well below the level that would ignite our concern (if there is no a dump resistance in the circuit).

So, the conclusion for the Part 1.1 (a quench occurs in the main coil) of this study is that the coil is quite safe to operate at any level of current without elaborate protection. Nevertheless, one must pay attention to timely recognize a quench event and make a power supply off.

1.2 Quench in one of the bucking coils

Because the main coil connected in series with the bucking coils, relatively high energy can dissipate in a relatively small volume of bucking coil resulting in an elevated coil temperature.

1.2.1 Quench occurs in the point of the maximum field

The initial quench location is on the inner side of each bucking coil, approximately in the middle of the side (layer #23, turn #10). Fig. 6 shows time profiles of the coil current, maximum temperature, and the coil resistance. Fig. 7 displays the final temperature after quench and a layer voltage-to-ground time profile. Two columns correspond to two different settings of the initial current:

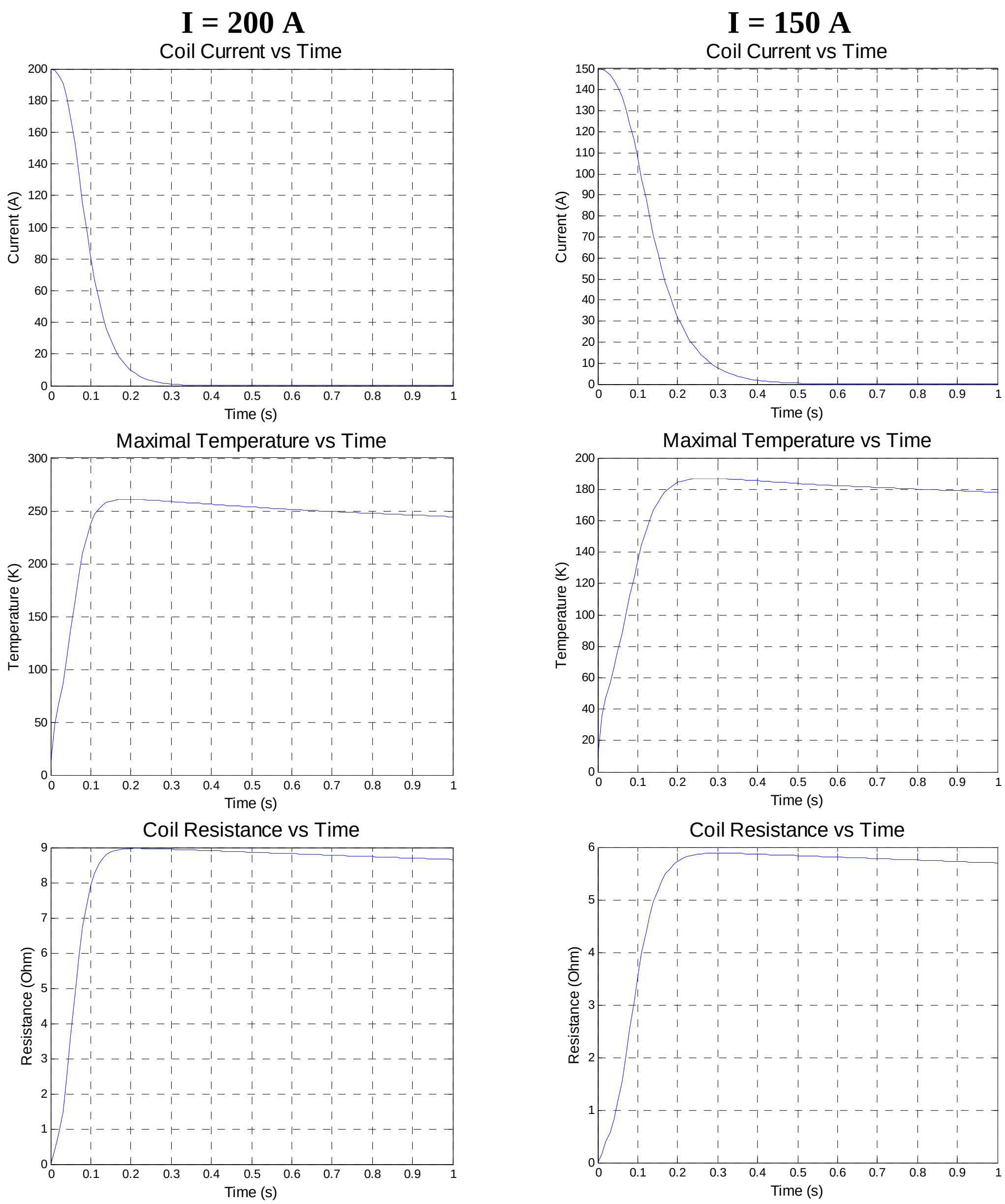


Fig. 6. Time profiles of the current, maximum temperature, and the resistance of the bucking coil. Quench starts at the point of the maximum field.

I = 200 A **I = 150 A**

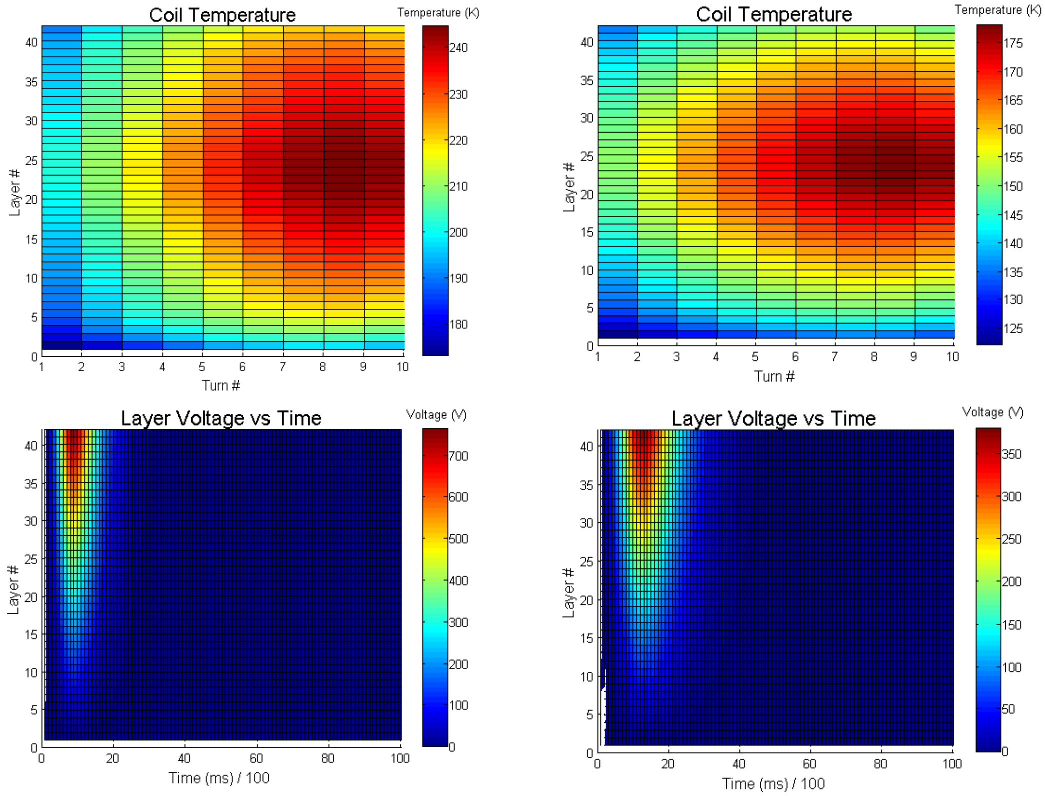


Fig. 7. Final temperature in the bucking coil and voltage to ground during quenching. Quench starts at the point of the maximum field.

In this case, the Bucking Coil temperature reaches ~ 260 K at 200 A (~ 190K at 150 A), which is relatively high. Voltage is maximal at the outer layer (#42) and reaches 760 V at 200 A at ~ 80 ms after the start of quench propagation (see the layer voltage chart in Fig. 8).

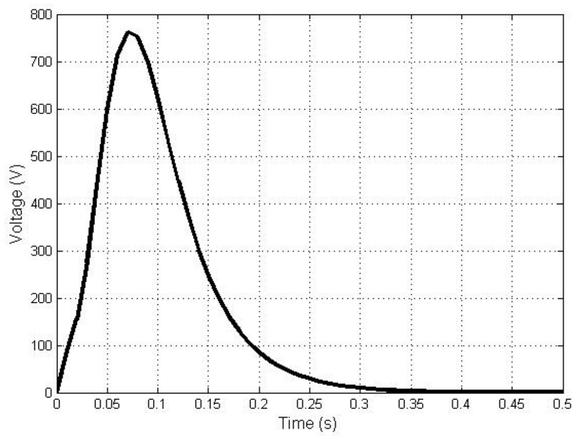


Fig. 8. Layer 42 voltage-to-ground as a function of time.

A relatively high temperature and voltage-to-ground makes it necessary to use a dump resistor in the current discharge circuit in order to remove part of the energy from the solenoid and optimize its value to limit voltage growth. Results of this study will be discussed in Part 2 of this note.

Besides high voltage to ground, we should closely watch voltage that can develop between two adjacent layers: the layer-to-layer voltage. Due to the regular winding pattern in the coils, this voltage is a sum of the voltages accumulated in the two adjacent layers. A time profile of this voltage as a function of time for the case when the quench starts in the area of the maximum field at 200 A is shown in Fig. 9.

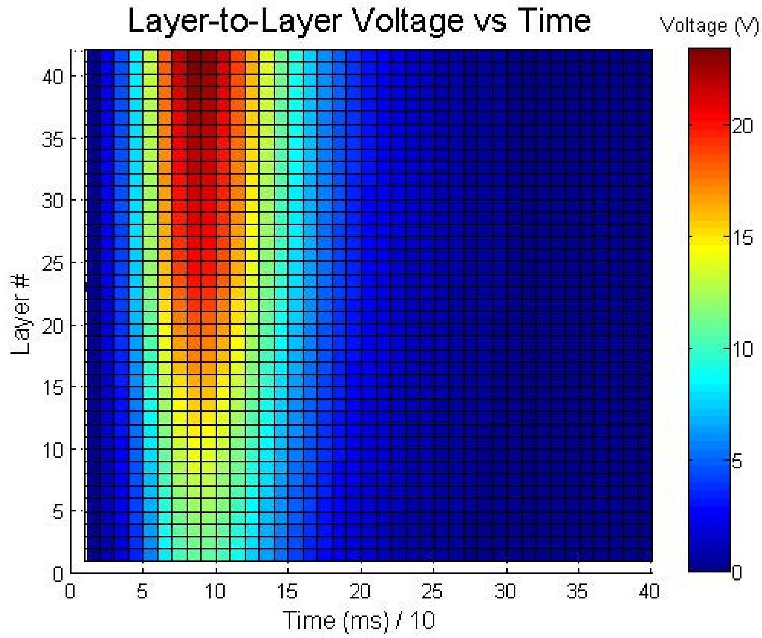


Fig. 9. Layer voltage as a function of time. Quench starts in the area of the maximum field; I0 = 200 A.

The maximum layer-to-layer voltage in this case is ~46 V. The location of the maximum layer voltage is close to the outer boundary of the coil, and the time of the onset of the maximum voltage is ~ 80 ms. Although the value of the maximum layer voltage can be tolerated, we will make a study to decrease this voltage in Part 2.

1.2.2 Quench occurs in the point of the minimum field

The initial quench location is on the outer side of each bucking coil, approximately in the middle of the side (layer #23, turn #1). Fig. 11 below shows time profiles of the coil current, maximum temperature, and the coil resistance. Fig. 12 provides temperature distribution after quench and a voltage-to-ground time profile. Two columns correspond to two different settings of the initial current:

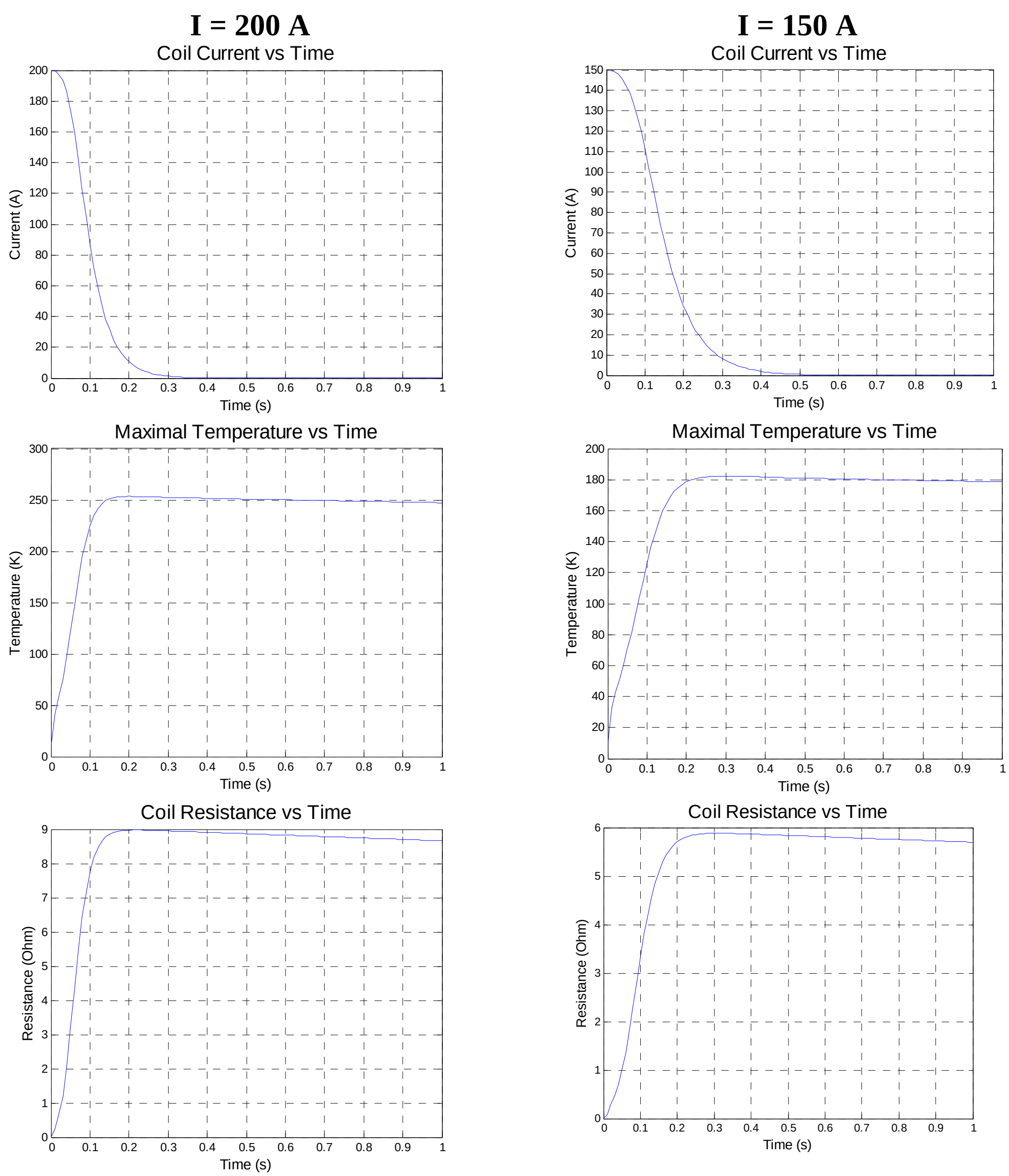


Fig. 10. Time profiles of the current, maximum temperature, and the coil resistance of the bucking coil. Quench starts at the point of the minimum field.

I = 200 A **I = 150 A**

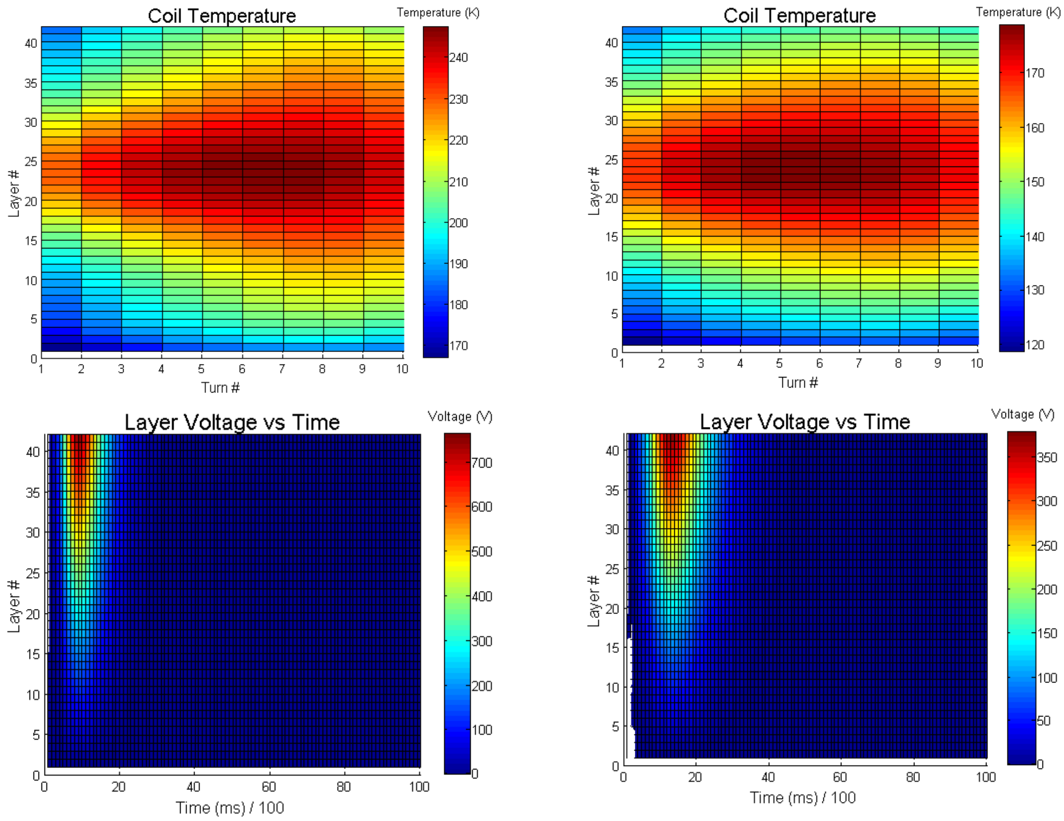


Fig. 11. Temperature in the coil after the quench and voltage to ground during quenching. Quench at the point of the minimum field.

If quench starts at the point of the minimum field the global behavior of the coil does not change relative to what we have seen if quench starts at the point of the maximum field. Temperature is slightly lower (250 K and 180 K at 200 A and 150 A respectively) and the maximum voltage stays almost unchanged.

1.3 Use of Quench Heaters for Coil Protection

Heaters are often used to raise temperature in certain areas of quenching coils. This helps to make heat deposition more uniform. Preliminary quench heater study was made in [6]. In order to study the efficiency of quench heaters in our case, the option was added to the quench analysis software. This option provides possibility to insert heaters at any point inside the coil. Shown in Fig. 13 are charts for coil temperature and strand resistance in the bucking coil at 1 ms and 20 ms after quench at the point of the maximum field. The heaters provide temperature rise in the coil beyond the critical temperature in 1 ms after quench detection.

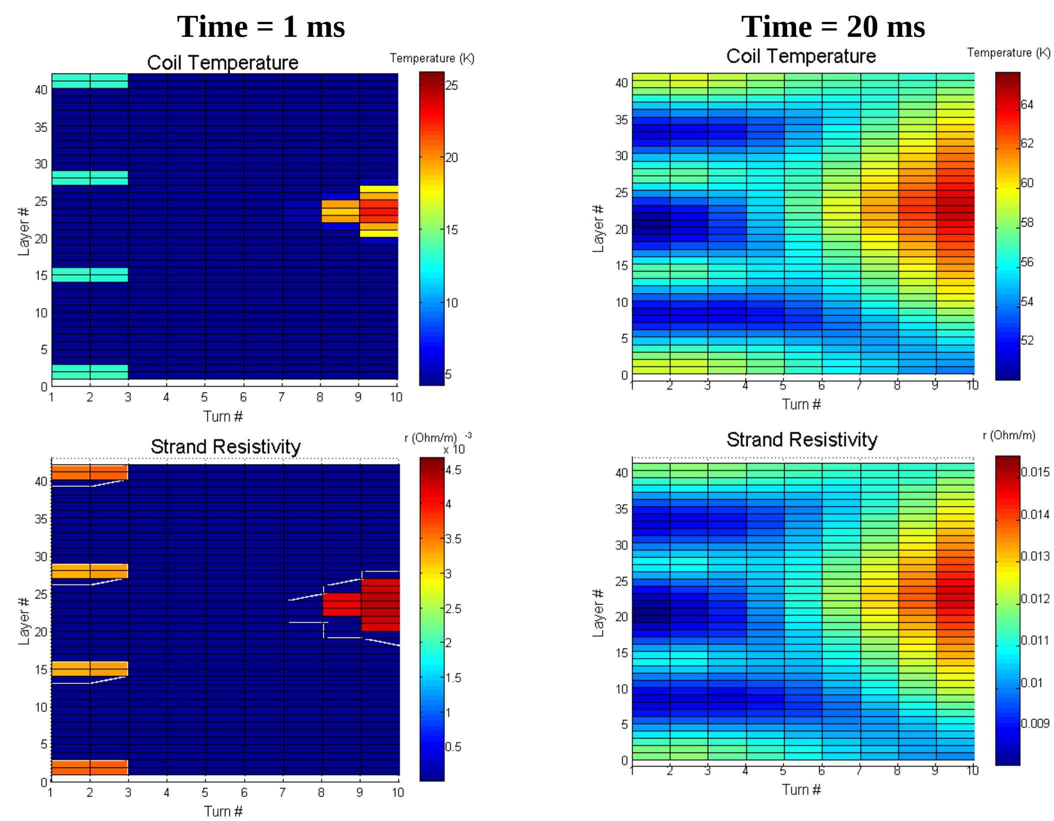


Fig. 12. Coil temperature and strand resistivity in the bucking coil at 1 ms and 20 ms after quenching. The quench occurs at the point of maximum field of the bucking coil; I0 = 200 A

Heaters were placed at different locations in the quenching coil and different power was provided to the heaters. The results show that the maximum temperature of the quenching coil just weakly depends on the presence of the heaters. Therefore, using the haters in the quenching coil does not seem promising. **Using the heaters in the coils of the solenoid that do not quench is another option that needs to be investigated**. Unfortunately, the existing software does not provide us this option, so some modifications of the software must be considered.

1.4 Intermediate conclusion

The results of this study show that, if no dump resistance is used in the circuit, the most dangerous situation from the point of view of quench protection can happen when quench occurs in one of the bucking coils at the maximum current of ~ 200 A. In this case, the temperature of the coil can reach ~ 260 K and the maximal voltage is ~ 760 V.

Initial quench location does not make much of a difference, resulting in very similar maximum temperature and voltage.

The additional study showed that quench heaters are ineffective in decreasing maximum coil temperature if the heaters are used in the quenching coil. Additional study is needed to investigate other options.

Use of a dump resistor in the current discharge circuit can help to reduce the maximum temperature in the coil; an increase of the maximum voltage in the coil can be an undesirable result of this use though. Special study will be devoted to this issue in the second part of this note.

2 Using a dump resistor for protection of focusing solenoids

In the first part of this note, we modeled quench propagation in the main and bucking coils in situations when quench initially occurred in points of maximum or minimum field. According to this analysis the worst case scenario happens when quench starts in one of the bucking coils. The results of modeling with the initial quench points in the area of maximum and minimum field show almost no difference in maximum temperature and voltage. When quench starts at the point of the maximum field, there is slightly higher maximum coil temperature and when quench starts at the point of minimum field, there is slightly higher maximum layer voltage-to-ground. Taking the said into the account, all further modeling will be done for the case when quench occurs in bucking coil in the area of maximum field. In this case, if no dump resistor is used, the maximum temperature in the bucking coil is approaching 260 K and the voltage level on the outer layer of the coil reaches approximately 760 V. The maximum temperature in the coil can be made lower if to use external (dump) resistance to remove part of the energy out of solenoid. In addition, right choice of a place where to make ground connection can help in keeping voltage to ground low at any point of the circuit.

According to study made in [2], there are two basic discharge circuit configurations. These configurations will be analyzed in this note.

2.1 First circuit configuration

The first discharge circuit configuration is shown in Fig. 13:

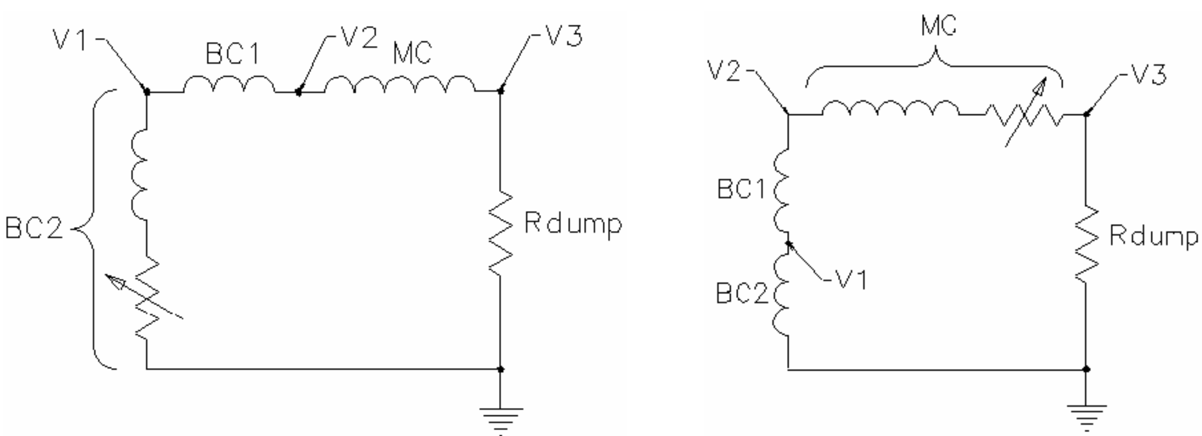


Fig. 13: Circuit configuration #1: a) quench in the bucking coil; b) quench in the main coil.

For this configuration, the ground connection is made between the bucking coil and the dump resistor. V1, V2, and V3 are voltages in the corresponding points relative to the ground after quench develops. While analyzing the process of quenching, we will use a discharge circuit from Fig. 13 (“a” or “b”) and scan the value of the dump resistor starting from Rdump = 0. In the cases when quench happens in the bucking or in the main coil, voltages V1, V2, V3, and the maximum voltage in the quenched coil will be found as well as the maximum coil temperature. Also, a fraction of energy dissipated in the dump resistor is an important property to know. The total energy absorbed by the dump resistor (***E***) should be compared with the energy stored in the system before the quench ***E0*** = Ltot*I0^2 / 2 = 8280 J, where Ltot is a sum of the inductances of all the three coils in the solenoid. In the case of SS-1 solenoid Ltot = Lmain + 2*Lbuck = 0.3877 + 2*0.0131 = 0.4139. The energy extraction efficiency is a ration ***E/E0***. It is assumed that the current in the Fig.13 circuit flows counterclockwise, so the resistive part of the voltage seen in the quenching bucking coil (relative to the ground) is positive.

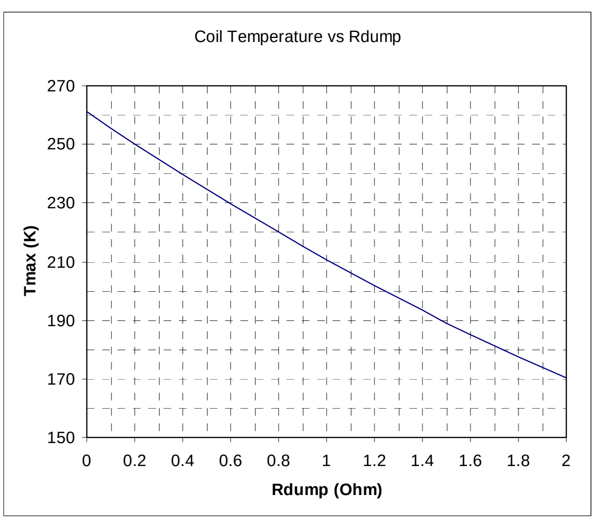
2.1.1 Quench occurs in the second bucking coil (BC2)

Let's consider a quench in the second bucking coil (BC2), which is the closest to the ground. The location of the quench starting point is on the inner side of each bucking coil, approximately in the middle of the side (layer #23, turn #10) where magnetic field has a maximum. This modeling was made by using modified MATLAB-based program for quench propagation analysis [3]. Table 1 provides the data corresponding to quenching BC2.

Table 1: Quench in the BC2 in case of first circuit configuration

Rdump (Ohm)	V1m (V)	V2m (V)	V3m (V)	Tm (K)	Rcoilm (Ohm)	E (J)	Efficiency
0.0	763	738	0	261.2	8.98	0	0.000
0.2	711	687	-40	250.2	8.53	547	0.066
0.4	662	638	-80	239.8	8.10	1070	0.129
0.6	615	593	-120	229.7	7.69	1568	0.189
0.8	572	550	-160	220.0	7.29	2042	0.247
1.0	531	509	-200	210.7	6.90	2490	0.301
1.2	492	471	-240	201.8	6.54	2914	0.352
1.4	456	436	-280	193.3	6.18	3314	0.400
1.6	422	402	-320	185.3	5.84	3691	0.446
1.8	390	371	-360	177.5	5.52	4043	0.488
2.0	361	342	-400	170.2	5.20	4372	0.528

Graphs in Fig. 14 below illustrate the data in Table 1; they show how the maximum temperature in the coil and the maximum coil resistance change with the value of the dump resistor.



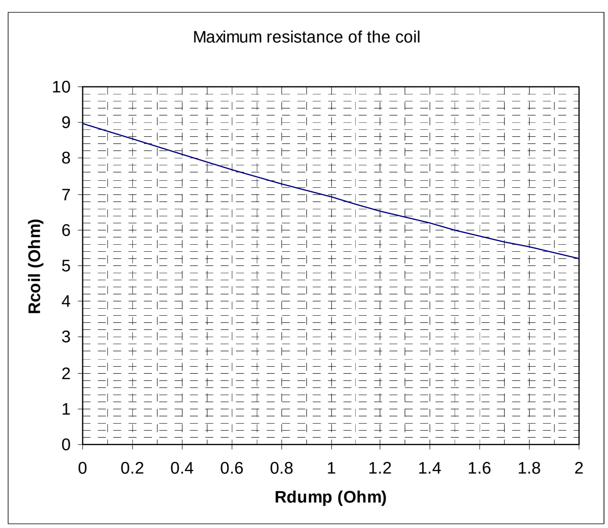


Fig. 14. Maximum temperature in the BC2 and the coil resistance as functions of the dump resistor value.

As expected, the temperature drops when the value of the dump resistor grows because of the growth of the energy removal efficiency; Fig. 15 shows the corresponding graph.

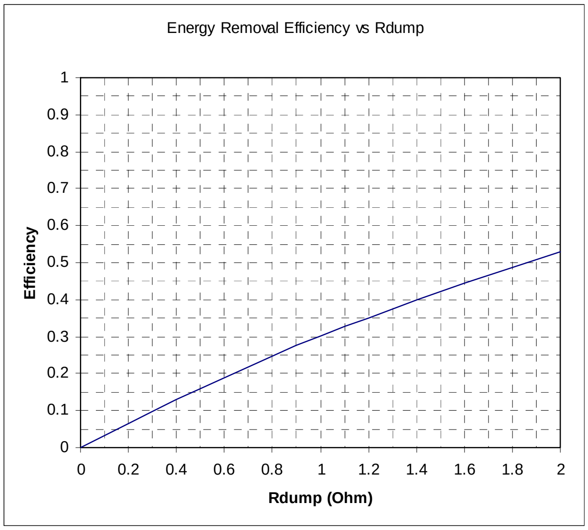


Fig. 15. Energy removal efficiency as a function of the dump resistor value.

To avoid appearance of internal stress because of high temperature gradients inside the solenoid (and also save some LHe), lower final temperature is preferred, so one would tend to increase Rdump if the voltage V3 can still be tolerated. The temperature growth correlates with the growth of the resistance of the coil after quenching.

Maximum voltages in different points of the circuit in Fig. 13a are shown in Fig. 16 as functions of Rdump. Here ABS(V3m) means absolute value of the maximum voltage at V3 tap.

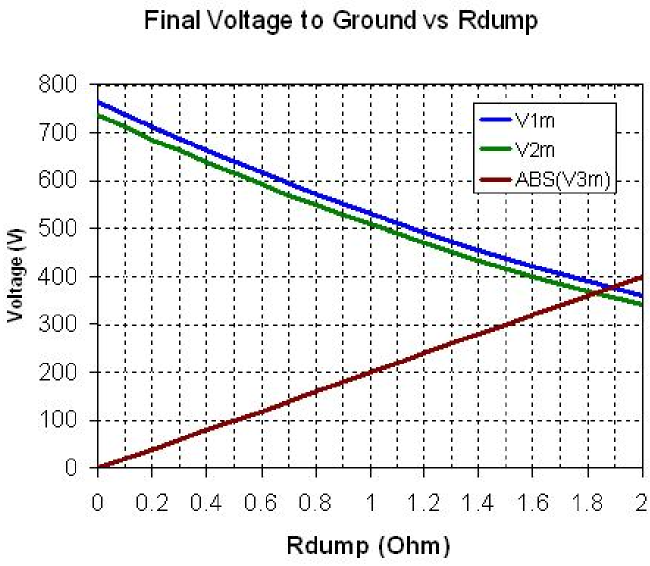


Fig. 16. Maximum voltage levels at different points of the circuit in Fig. 13a.

When Rdump < 1.9 Ohm, higher voltage is expected between BC1 and BC2. If Rdump ≥ 1.9 Ohm, a part of the main coil closest to the dump resistor sees higher voltage, which increases as Rdump increases.

The minimum voltage level in the circuit is ~ 380 V and is reached at Rdump = 1.9 Ohm. Extraction efficiency in this case is ~ 0.5 and the maximum temperature is ~175 K.

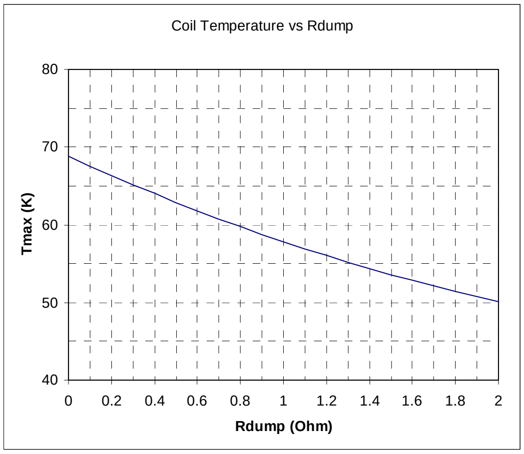
2.1.2 Quench occurs in the main coil

Table 2 shows data corresponding to the quenching main coil.

Table 2: Quench in the MC in case of first circuit configuration

Rdump (Ohm)	V1m (V)	V2m (V)	V3m (V)	Tm (K)	Rcoilm (Ohm)	E (J)	Efficiency
0.0	-10	-21	0	68.8	3.1	0	0.000
0.2	-10	-21	-40	66.4	2.8	1031	0.125
0.4	-10	-21	-80	64.0	2.6	1949	0.235
0.6	-10	-21	-120	61.8	2.4	2760	0.333
0.8	-10	-21	-160	59.8	2.2	3474	0.420
1.0	-11	-21	-200	57.8	2.1	4099	0.495
1.2	-11	-22	-240	56.1	1.9	4643	0.561
1.4	-11	-22	-280	54.4	1.8	5115	0.618
1.6	-11	-23	-320	52.9	1.7	5528	0.668
1.8	-12	-24	-360	51.4	1.6	5884	0.711
2.0	-13	-26	-400	50.1	1.6	6195	0.748

The data is illustrated in the graphs below.



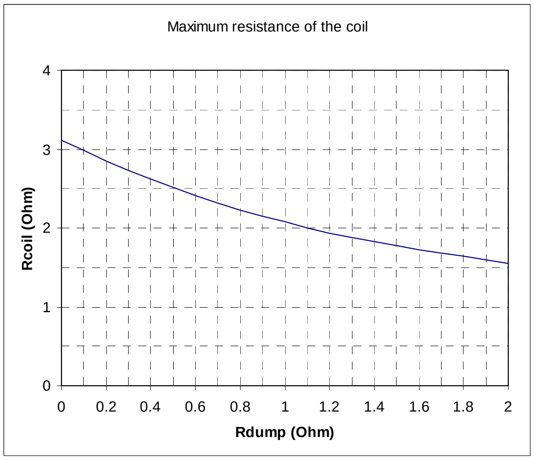


Fig. 17. The maximum temperature in the MC and coil resistance as functions of the dump resistor value.

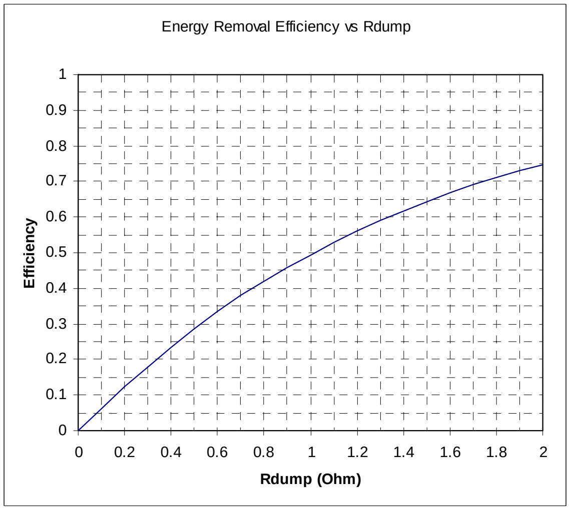


Fig. 18. Energy removal efficiency as a function of the dump resistor value.

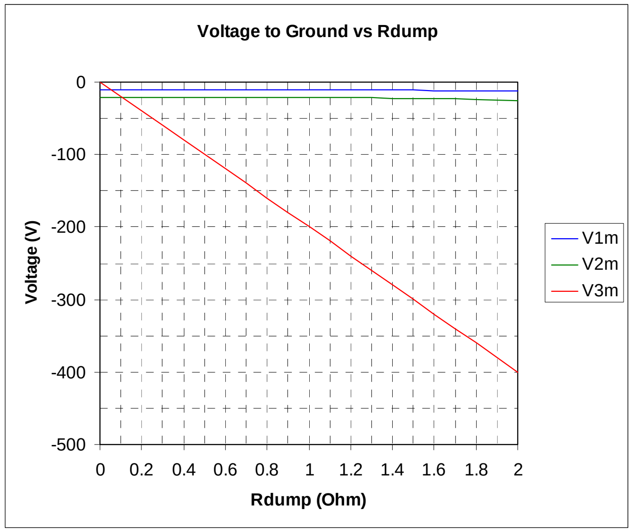


Fig. 19. Maximum voltage levels at different points of the circuit in Figure 2-1b.

Comparing Fig. 16 and Fig. 19, we can conclude that when Rdump < 1.9 Ohm, voltage in the bucking coil can be high only if quench occurs in one of the bucking coils. When Rdump ≥ 1.9 Ohm, the voltage on the main coil is higher wherever the quench occurs and tends to increase with Rdump. Increasing Rdump, we can get greater energy removal efficiency and lesser temperature of the coil, but an attention must be paid to the growth of the voltage at V3.

2.2 Second circuit configuration

The second circuit configuration to be investigated is when the ground is made between the dump resistance and the main coil. In this case, behavior of the coil resistance and maximum temperature do not change. Also the energy removal efficiency stays the same. Voltages at different points of the circuit (see Fig. 20) change though.

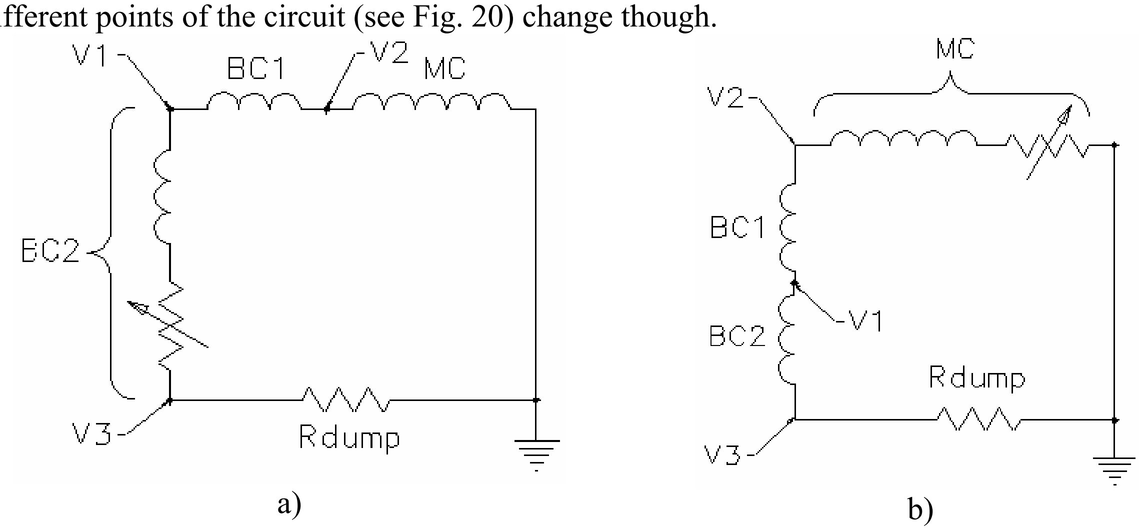


Fig. 20. Circuit configuration # 2: a) quench in the bucking coil; b) quench in the main coil.

2.2.1 Quench occurs in the second bucking coil (BC2)

Table below provides data related to quenching in the bucking coil.

Table 3: Quench in the BC2 in case of second circuit configuration

Rdump (Ohm)	V1m (V)	V2m (V)	V3m (V)	Tm (K)	Rcoilm (Ohm)	E (J)	Efficiency
0.0	763	738	0	253.5	9.0	0	0.000
0.2	732	708	40	242.5	8.5	578	0.070
0.4	704	681	80	231.8	8.1	1130	0.137
0.6	677	655	120	221.3	7.6	1657	0.200
0.8	654	632	160	211.2	7.2	2157	0.260
1.0	634	613	200	202.2	6.8	2633	0.318
1.2	616	596	240	193.2	6.4	3080	0.372
1.4	600	580	280	184.7	6.0	3504	0.423
1.6	585	566	320	176.5	5.6	3900	0.471
1.8	572	553	360	168.7	5.3	4270	0.516
2.0	561	543	400	161.3	5.0	4615	0.557

Graphs in Fig. 21 illustrate the case.

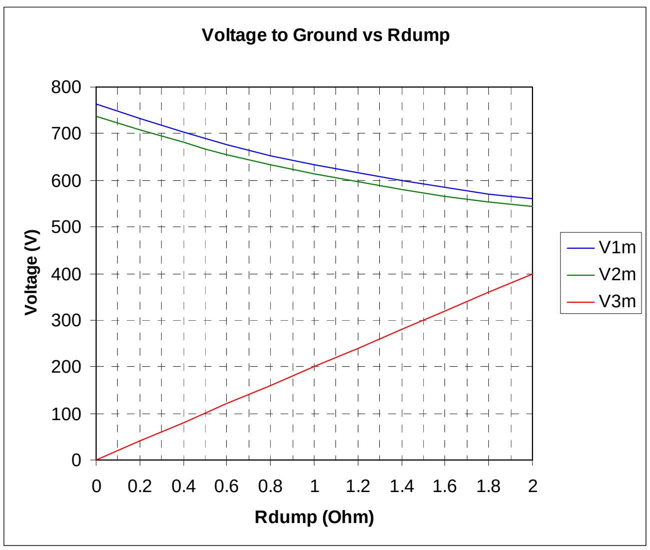


Fig. 21. Maximum voltage levels at different points of the circuit in Fig. 20a.

Although a value of the dump resistance corresponding to the minimum voltage is not seen in Fig. 21, we can use obvious extrapolation get the minimum voltage in the circuit at the level of ~500 V (at Rdump ≈ 3 Ohm). The maximum temperature did not change much in comparison with the case of first circuit configuration, but higher maximum voltage is expected in the second circuit at the same temperature.

2.2.2 Quench occurs in the main coil

Table 4 presents data in the case when the quench starts in the main coil.

Table 4: Quench in the MC in case of second circuit configuration

Rdump (Ohm)	V1m (V)	V2m (V)	V3m (V)	Tm (K)	Rcoilm (Ohm)	E (J)	Efficiency
0.0	-10	-21	0	68.8	3.1	0	0.000
0.2	39	37	40	66.4	2.8	1031	0.125
0.4	77	75	80	64.0	2.6	1949	0.235
0.6	116	112	120	61.8	2.4	2760	0.333
0.8	155	150	160	59.8	2.2	3474	0.420
1.0	194	187	200	57.8	2.1	4099	0.495
1.2	232	225	240	56.1	1.9	4643	0.561
1.4	271	262	280	54.4	1.8	5115	0.618
1.6	310	300	320	52.9	1.7	5528	0.668
1.8	349	337	360	51.4	1.6	5884	0.711
2.0	387	375	400	50.1	1.6	6195	0.748

Graphs in Fig. 22 illustrate the case.

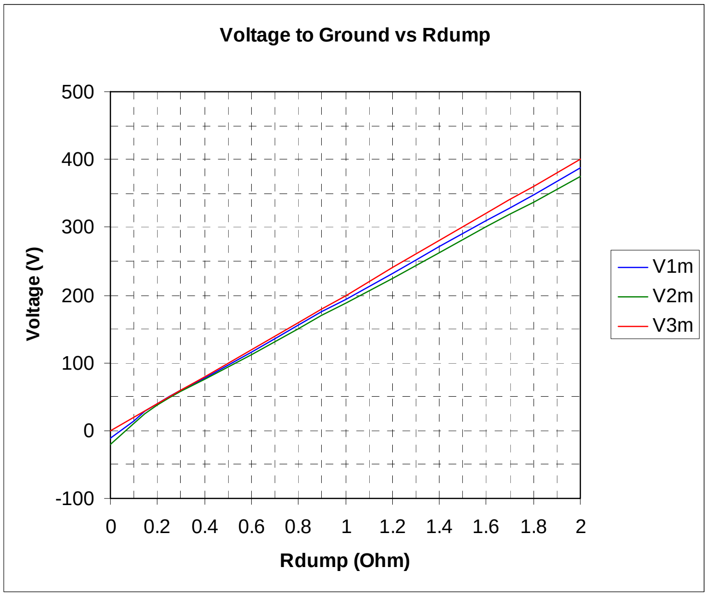


Fig. 22: Maximum voltage levels at different points of the circuit in Fig.20b.

In this case, voltages tend to increase following Rdump (with the exception of narrow zone when Rdump is close to zero).

2.3 Intermediate conclusion

Because making circuit in accordance with Fig. 20 results in higher voltages in all the elements, it is recommended to use Fig. 13 for making connections during testing. It is also desirable to use dump resistance greater than 1.9 Ohm and connect the outer layer of the main coil with the dump resistance.

3 Conclusion

In this note a study of quench propagation and related protection issues is described made for HINS Linac Front End SS-1 Section Focusing Solenoids. The study has been made with the use of a modeling software.

In Part 1 it is shown that the worst case scenario (maximum temperature and voltage) happens when quench starts in one of the bucking coils. We can also stress an ineffectiveness of using quench heaters in the quenching coil for quench protection.

In Part 2 the optimal quench protection circuit configuration is found. According to this analysis, circuit configuration shown in Fig. 13 should be used during testing. Optimal value of the dump resistor is Rdump ≈ 1.9 Ohm. In the worst case (quench in the bucking coil) with Rdump = 1.9 Ohm the expected maximum temperature reaches 175 K and maximum voltage in circuit reaches 380 V. If to increase Rdump, we can expect greater energy removal and lower coil temperature, but the maximum voltage tends to grow with Rdump.

Notation conventions

BC1 – first (left side) bucking coil
BC2 – second (right side) bucking coil
LHe – liquid Helium
MC – main coil
Rdump – value of dump resistance
Rcoilm - maximum coil resistance
Tm – maximum temperature of the coil
V1m – maximum voltage at V1 tap
V2m – maximum voltage at V2 tap
V3m – maximum voltage at V3 tap

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